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THAWING AND DIFFERENTIAL SETTLEMENT CLOSE TO OIL WELLS THROUGH PERMAFROST

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by

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INTRODUCTION

Recent discoveries of oil resources in Alaska and the Canadian Arctic have focussed attention on the problems of drilling production wells through permafrost. The problems have recently been reviewed by Koch [3]*. On the Alaskan North Slope the ground is frozen to a depth of some 600 m. Oil flowing in a well is at a temperature of between 60 and 85°C. Unless special measures are taken to insulate or refrigerate the well casing, heat conducted outward from the casing will in time thaw the soil in an annular region, to a radius of the order of 15 m in 10 years. If the thawed soil cannot carry the overburden loads acting on it, it will consolidate, and the consequent settlements may induce undesirably large movements at the surface. More importantly still, the soil is then tending to settle vertically relative to the casing, and therefore shear tractions act downward on the casing, and induce in it compressive stresses which may be large enough to make it buckle. Since insulation and refrigeration are extremely costly, and may not entirely suppress thawing, it becomes important to estimate the axial forces and settlements that occur in an uninsulated well.

The ~~present~~ paper puts forward a preliminary analysis, whose purpose is to identify the factors which determine settlements and casing stresses, and to find out what information is needed for a more precise evaluation. Bold idealizations will be made in order to isolate primary from secondary factors : thus, for example, no account is taken of the variation with depth of the initial temperature of the undisturbed permafrost layer. The heat transfer problem is briefly considered first ; simple models of thaw consolidation and arching follow, and their implications for thawing around a well are then examined.

HEAT TRANSFER

The most striking feature of the geometry of the system is its great length (of the order of the depth of the well) by comparison with its radius (of the order of the thaw radius), an important simplification which will frequently be made use of. It is also axially symmetric. The heat transfer problem, which determines the radius of the thaw annulus, is quite straightforward, and will be outlined very briefly. If the permafrost layer is initially uniform in temperature, ice content, and thermal properties, and the oil temperature changes by a negligible amount as the oil rises in the well, then heat flow around the well is two-dimensional and axisymmetric,

* Numbers in square brackets refer to the list of references.

and the radial distribution of temperature θ is governed by

$$\frac{1}{\kappa}\frac{\partial\theta}{\partial t} = \frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\frac{\partial\theta}{\partial r} \tag{1}$$

where r is radius from the well axis, t is time, and κ is thermal diffusivity, assuming that heat convection can be neglected. At the casing surface $r = a$ and the temperature is θ_1 , supposed maintained equal to the oil temperature. The initial temperature of the permafrost is θ_o. The thaw annulus radius increases with time, and at t is R(t); the thaw front temperature is θ_F. If the energy required to thaw unit volume of soil is Λ , a heat balance at the thaw front gives

$$-\Lambda\frac{dR}{dt} = \left[k\frac{\partial\theta}{\partial r}\right]_{r=R} \tag{2}$$

where k is the thermal conductivity and the right-hand term is the discontinuity in $k\partial\theta/\partial r$ at R. A simple approximate solution, applicable to soils of large ice content, follows if $\kappa \to \infty$; physically, this is to say that the influence on the temperature distribution of the 'latent heat' contribution to the heat balances, corresponding to the energy required to thaw the soil, is large by comparison with that of the 'specific heat' contribution, corresponding to the heat required to warm the soil from θ_o to θ_F before thawing and from θ_F towards θ_1 afterwards. At any instant, the temperature distribution is then identical with the steady flow distribution for a thaw radius fixed at the current thaw radius R. It can then easily be shown that the thaw radius R is related to the time t from the start of production by

$$t = \frac{a^2\Lambda}{k(\theta_1-\theta_F)}\{\tfrac{1}{2}(R/a)^2(\ln(R/a)-\tfrac{1}{2}) + \tfrac{1}{4}\} \tag{3}$$

Taking typical values of $\theta_1-\theta_F$ = 80 degC, a = 0.2 m, Λ = 110 MJ/m^3 and k = 2 W/m degC (values appropriate for silt at 20 % ice content), equation (3) gives a thaw radius of 15 m after 9.4 years. This approximate solution is consistent with results of numerical calculations reported by Koch [3]. neglect of specific heat leads a slight overestimate of thaw radius; this can be corrected by the method of Pekeris and Slichter [6].

A MODEL OF THAW CONSOLIDATION

It may happen that a frozen soil is fully consolidated in its natural state, in the same way as a fully saturated unfrozen soil in equilibrium with a ground water level at the surface. The interparticle ice then transmits a hydrostatic stress, equal to the depth multiplied by the ice density, and the remainder of the overburden load is carried by an effective stress transmitted between the soil particles. Since the ice is then not subjected to shear stress, it does not tend to creep and redistribute the total stress. If a layer of such a soil is thawed at constant void ratio, it does not tend to deform, because the effective stress remains everywhere the same. More commonly, however, the fully consolidated state has not been reached, and a soil thawed under its original overburden does tend to deform. The effective stresses existing at its initial void ratio are not large enough to carry the applied load, so that immediately after thawing pore pressures are generated and carry part of the total stress. As they diffuse, the soil's void ratio decreases and the effective stresses increase.

To make these ideas more precise, consider a uniform sample of frozen soil loaded in a consolidometer. What happens when it is thawed can be illustrated in Figure 1, where the voids ratio is plotted against vertical stress, supposing consolidation to occur under conditions of zero lateral strain. Initially the voids ratio is e_1 and the total stress q, and so the state can be represented by point 1. The curve ac relates voids ratio to effective stress for the thawed soil in a conventional consolidation test. If the soil is thawed rapidly, without any change of voids ratio, the effective stress is p and a pore pressure q-p is induced; the soil state is then represented by point 2. Pore pressures diffuse at a rate controlled by the coefficient of consolidation, the point representing the soil state moves from 2 to 4 along ac, and the voids ratio falls from e_1 to e_4. If the soil remains saturated on thawing the void ratio falls, in the ratio of the densities of ice and water, and the state immediately after thaw is represented by point 3. In either case the final state is the same, and the thaw strain is $(e_1-e_4)/(1+e_1)$. Curve ac can be determined by a test on a thawed sample of soil, and can be used to find what pore pressures are induced by a certain loading history. Consolidation theories based on models of this type have been analysed by Tsytovich [9], Zaretskii [10], Morgenstern and Nixon [5] and others, but no detailed comparison with experiment has been published.

THAW CONSOLIDATION AROUND A WELL

The implications of this simple model for settlement in the thaw annulus are now examined. Two extreme cases are considered first. In one extreme case the annulus is considered as an isolated column of soil which gets no support from the surrounding still-frozen soil, but resists gravity by consolidating vertically and thus increasing effective stress. In the other extreme case an arching action transmits to the surrounding frozen soil all that part of the thawed soil's submerged weight which cannot be resisted by the initial vertical effective stress. Neither extreme case properly represents the actual conditions, but studying them separately throws light on the significant aspects of the problems. It will become clear that the arching effect must dominate the behaviour of the central portion of the thaw annulus, and that the consolidation model determines the behaviour of the ends.

Suppose first that the thaw annulus is not supported by the surrounding soil, and that shear stresses transmitted between it and the casing have a neglible effect on the stress in the soil. If the annulus is thawed rapidly, the total stress across a horizontal plane is unit weight of the soil integrated over the depth to the plane. The effective stress is the effective stress that existed in the frozen state; the rest of the total stress is carried by a pore water pressure, of which part is the hydrostatic pressure (the product of the depth and the water density) and the remainder an excess pore water pressure. The distribution of stress is illustrated schematically in Figure 2. As the soil consolidates the annulus shortens, and, if the displacement at the base of the annulus is negligible, the displacement at depth z is

$$\int_z^L \varepsilon_T(z)\, dz$$

where $\varepsilon_T(z)$ is the thaw consolidation strain under an effective stress

$$\int_0^z (\gamma(z)-\gamma_w)\, dz$$

$\gamma(z)$ being the total unit weight of soil at z and γ_w the unit weight of water. If the casing were to follow these displacements, its axial strain would be of the order of ε_T. If the soil slips downward relative to the pipe, the shear traction downward on the casing is $\mu K_o(\gamma-\gamma_w)z$, where μ is a coefficient of friction and K_o a ratio of vertical to horizontal stress, and it follows that the axial stress in a casing of thickness t at depth z is

$$\sigma_c = \frac{1}{t}\int_0^z \mu K_o(\gamma-\gamma_w)\ z\ dz \tag{4}$$

If $\mu = 0.2$, $K_o = 0.6$, $\gamma-\gamma_w = 8\ kN/m^3$ and $t = 20$ mm, say, this stress reaches $240\ N/mm^2$ at a depth of 100 m, and becomes unacceptably large at greater depths.

Large axial stresses in the casing therefore certainly develop if the soil is not supported by arching. The time over which these stresses develop is however governed by pore pressure diffusion, and may be very long if the thawed soil is impermeable. Since the soil outside the thaw annulus is frozen, water cannot diffuse laterally, but must flow upward to the surface or downward to the unfrozen soil below the permafrost base. The drainage paths are of the order of L/2. Consolidation theory (see, for example, Schofield and Wroth[7]) then shows that the time at which half the ultimate settlement has developed is of the order of $0.2(L/2)^2/c_{vc}$, where c_{vc} is the Terzaghi coefficient of consolidation, the precise value of the numerical factor depending on the detailed initial distribution of pore pressure. If L is 600 m, and c_{vc} is $2 \times 10^{-8}\ m^2/s$ (a typical value for fine silt), this time is of the order of 3000 years. It follows that if the soil is medium silt or finer, settlements will develop too slowly to give rise to trouble within the life of the well. Even if the soil is inhomogeneous, the significant times will be governed by the thicknesses and permeabilities of the least permeable layers.

This calculation draws attention to the importance of thinking about pore pressures and the movement of water within the thaw annulus. Harmful effects could occur, for instance, if artesian pressures existed below the permafrost base. Though it might be possible to seal the well casing, it would be difficult to seal the whole thaw annulus against these pressures. Water would then flow upwards in the annulus, very much increasing the thaw rate (by introducing convective heat transfer) and reducing the stability of the thawed soil. A similar mechanism has been suggested as that responsible for the formation of pingos [4].

ARCHING

In the other extreme simple case, the submerged weight of the thaw annulus is supported partly by the effective stresses that existed before thawing and partly by shear stresses transmitted laterally. Suppose the

submerged unit weight to be $\gamma-\gamma_w$, so that at depth z the total stress less the equilibrium pore pressure is $(\gamma-\gamma_w)z$, and let the pre-existing effective normal stress across a horizontal plane be $\lambda(\gamma-\gamma_w)z$, where λ is less than unity. A soil for which λ were 1 would be fully consolidated in the frozen state, in the sense discussed earlier. An element of height dz between horizontal planes, illustrated in Figure3, can then remain in equilibrium on thawing, without any increase in effective stress across a horizontal plane, if its edges are supported by a shear stress $(\pi/2)R(1-\lambda)(\gamma-\gamma_w)$ at the outer radius of the thaw annulus; the required shear stress increases linearly with radius. The ratio of this maximum shear stress to the effective stress $\lambda(\gamma-\gamma_w)z$ across horizontal planes is

$$(\pi/2)\ \frac{R}{z}\ \frac{1-\lambda}{\lambda}$$

If, for instance, $\lambda = 0.5$, the ratio is $(\pi/2)R/z$, and becomes less than 0.3 if z is greater than 5.2R. In a typical granular soil, this ratio of shear to normal effective stress can be sustained by the soil after strains of the order of 0.02 have developed (see, for example, Bransby [1]). Since in practice L/R is of the order of 40, most of the thaw annulus can be supported by arching, without any necessity for substantial increases in effective stress. In the uppermost part of the annulus, however, arching is not completely effective, because the pre-existing effective stresses are too small. The above analysis follows the classical analysis of arching by Janssen [2].

The soil movements needed to bring the arching effect into play are very small. Displacements outside the thaw annulus are almost certianly negligible : they result from the extra loads transmitted to the surrounding frozen soil by the shear tractions at the thaw front, and the corresponding stresses decrease rapidly with increasing radius, certainly faster than r^{-1}. If the vertical displacement at the centre of the annulus is Δ, and it is assumed that shear strains increase linearly with shear stress, the shear strain at the outer boundary of the thaw annulus is $2\Delta/R$. If this is to be 0.02, Δ is 0.01 R , or 0.15 m for a 15 m thaw radius; this would be the settlement at a depth of 5.2 R (following the approximate analysis above), or 80 m. Since the ratio of the maximum shear stress to the effective normal stress decreases with increasing depth z, the strains needed to develop this stress ratio also decrease with depth, and so the

vertical displacements decrease.

If the casing displacements are the same as the soil vertical displacements at the centre of the thaw annulus, the axial strain in the casing is the derivative of the displacement with respect to depth. Assuming that the shear strain needed to develop a shear stress to normal effective stress ratio of 0.3 is 0.02, and that this strain is proportional to the stress ratio, the central displacement is given approximately by

$$\Delta = 0.1 \frac{1-\lambda}{\lambda} \frac{R^2}{z} \qquad (5)$$

and so the axial compressive stress in the casing is approximately

$$\sigma_c = 0.1 \frac{1-\lambda}{\lambda} (R/z)^2 E \qquad (6)$$

if E is the casing Young's modulus. As has been shown earlier, this solution does not apply for small z. It predicts acceptably small casing stresses in the region where behaviour is dominated by arching action, unless λ is small.

INTERACTION BETWEEN ARCHING AND THAW CONSOLIDATION

When an annulus surrounding a well casing thaws in soil which is not fully consolidated, part of its weight cannot be carried by the existing interparticle forces and the corresponding effective stresses. It has been shown that arching can support most of the thaw annulus, and that quite small movements are sufficient to develop arching action, but that it is not effective in the uppermost part of the thaw annulus, to a depth of perhaps 5R. The situation is illustrated schematically in Figure 4. In the upper region the soil consolidates to a greater extent : part of the load is carried by arching and part by increased effective stresses. At the surface the axial strain in the soil is of the order of the thaw consolidation strain ε_t. Near the surface the shear tractions that the soil can transmit are small, and are not large enough to force the casing to follow the movements of the soil : the soil slips downwards relative to the casing, and the consequent increase of casing stress with depth is governed by equation (4). In the region dominated by arching, the casing can follow the soil movement, and the casing stress is given by equation (6). There is an intermediate region, in which the pipe does follow the movement

of the soil, but in which arching is only partly effective. Here the displacements Δ decrease with increasing depth (because the strain in the soil must be compressive), and the axial compressive strain $-d\Delta/dz$ also decreases with depth (because the necessary effective stress increment decreases with depth as arching becomes more important). It follows that in this transition region the axial compressive strain in the casing must also decrease with depth. The compressive stress decreases in the same way, and is always less than the stress given by equation (6). In this region the forces exerted on the casing by the soil must be upward, and the compressive stress in the casing reaches its greatest value at the point Y, at the upper end of the transition and the lower end of the region in which the soil slips downward relative to the casing. An upper bound on the maximum stress can then be found by supposing (6) to hold below Y and (4) to hold above it. For simplicity, assume that $\gamma-\gamma_w$ is uniform with depth; let $z = y$ at Y. Then, since the casing stress must be continuous at Y,

$$\mu K_o(\gamma-\gamma_w)y^2/2t = 0.1\,\frac{1-\lambda}{\lambda}\,(R/y)^2E \qquad (7)$$

and therefore

$$y/R = \left\{0.2\,\frac{1-\lambda}{\lambda}\,\frac{tE}{\mu K_o(\gamma-\gamma_w)R^2}\right\}^{1/4} \qquad (8)$$

If $t = 20$ mm, $\lambda = 0.5$, $E = 210$ kN/mm^2, $\gamma-\gamma_w = 8$ kN/m^3, $R = 15$ m, $K_o = 0.6$ and $\mu = 0.2$, then

$$y/R = 7.9$$

The corresponding casing stress is 340 N/mm^2 (49 000 lb/in^2). It is emphasised that this calculation leads to an upper bound on the maximum casing stress, and that it is not representative of any particular real case. The numerical coefficient 0.1 in (6) and on the right-hand side of (7) is not independent of material properties; in its derivation it was assumed that a shear strain of 0.02 is necessary to generate a stress ratio of 0.3.

These calculations are of course approximate, though they can be made more precise, but it many cases they may be enough to indicate that settlements have insignificant effects on the casing. It is interesting to note that the stresses predicted by this simple analysis are of the same order of magnitude as the results of an unpublished finite-element

analysis, apparently making different assumptions, which have been reported by Koch [3] and by Smith and Clegg [8].

The displacements predicted by the elementary arching analysis (equation (5)) only tend to zero asymptotically as z becomes large, whereas in fact there is probably no movement at all below the permafrost layer. There must be another region, at the base of the thaw annulus, in which slip between the soil and the casing allows the displacements to match. A small rise in casing compressive stress must occur, and is shown in Figure 4. It must be small, since all the displacements are small and the surrounding material is deformable enough to allow the small mismatch to be taken up.

CONCLUSION

What does this analysis suggest to be the most important field data needed for the assessment of settlements and casing stresses in a particular case ?

It is clearly extremely important to know how far the soil is from being fully-consolidated in its initial frozen state, that is, how far the overburden load is carried by effective stresses which already exist before thawing. If it is fully consolidated ($\lambda = 1$) settlements on thawing will be very small. If λ is nearly 1, arching will be very effective, large movements will only occur close to the surface, and casing stresses will be small. If λ is small, arching is much less effective. The extent of initial consolidation is a property of the site rather than of the soil type, and can only be directly determined by thaw consolidation tests on undisturbed cores, though important supporting evidence can come from geology and geomorphology.

Other properties are also important, but many of them can be estimated with sufficient accuracy from tests on disturbed samples. In particular, laboratory tests can be used to determine the relationship between stress ratio and strain which controls the amount of vertical movement necessary to develop arching. The natural state of stress in the ground is also important, but no work seems yet to have been done on initial stresses acting in permafrost.

The calculations above show that the thawing system is in many cases simple enough for useful conclusions to be based on concepts taken from elementary soil mechanics. One particular case has been examined, that of a completely uninsulated well, but the same principles can readily be applied to other cases, such as that of a well in which thawing close to the surface is suppressed by refrigeration and the casing is partly supported by axial tension. It would naturally be extremely valuable if th e conclusions could be tested by comparison with field observations on actual wells. Koch [3] has described a one-year test in which the thaw radius reached 6 m and no significant subsidence occurred. The results of longer-term tests will be of great interest.

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REFERENCES.

1. Bransby, P.L. "Stress and strain in sand caused by rotation of a model wall" Ph.D. dissertation, Cambridge University, England (1968).
2. Janssen, H.A. "Versuche über Getreidedruck in Silozellen" ("Experiments on grain pressure in silos"), Zeitschrift des Vereines deutsche Ingenieure (Berlin), 39, 1045-1049, (1895).
3. Koch, R.D. "The design of Alaskan North Slope production wells", Proceedings, Institution of Mechanical Engineers (London), 185, 989-1001, (1971).
4. Mackay, J.R. "Pingos of the Pleistocene Mackenzie River delta", Geographical Bulletin (Ottawa), 18, 21-63, (1962).

5. Morgenstern, N.R. and Nixon, J.F. "One-dimensional consolidation of thawing soils", Canadian Geotechnical Journal (Ottawa), 8, 558-565, (1971).

6. Pekeris, C.L. and Slichter, L.B. "Problem of ice formation", Journal of Applied Physics (Lancaster, USA), 10, 135-137 (1939).

7. Schofield, A.N. and Wroth, C.P. "Critical state soil mechanics", McGraw-Hill (London),(1967).

8. Smith, R.E. and Clegg, M.W. "Analysis and design of production wells through thick permafrost", paper presented to the Eighth World Petroleum Congress, Moscow, 1971.

9. Tsytovich, N.A. "Permafrost in the USSR as foundations for structures", Proceedings, Sixth International Conference on Soil Mechanics and Foundation Engineering (Montreal, 1965), Volume III, 155-167, University of Toronto Press,(1965).

10. Zaretskii, U.K. "Teoriya konsolidatsiya gruntov" ("Theory of the consolidation of soils"), Izdatel'stvo Nauka, Moscow (1967).

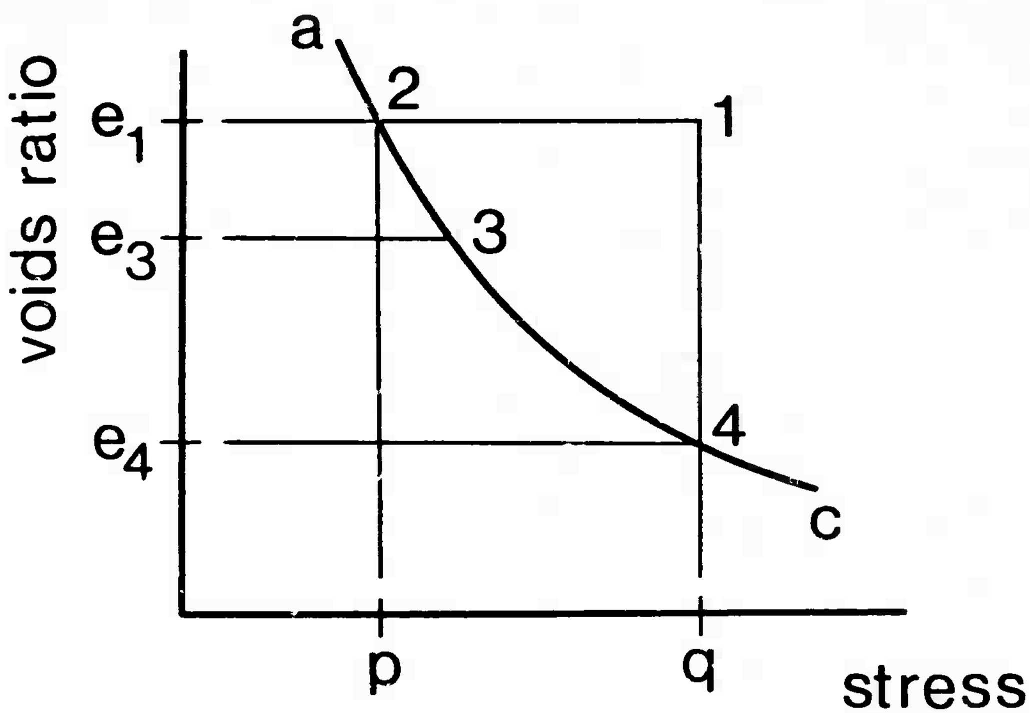
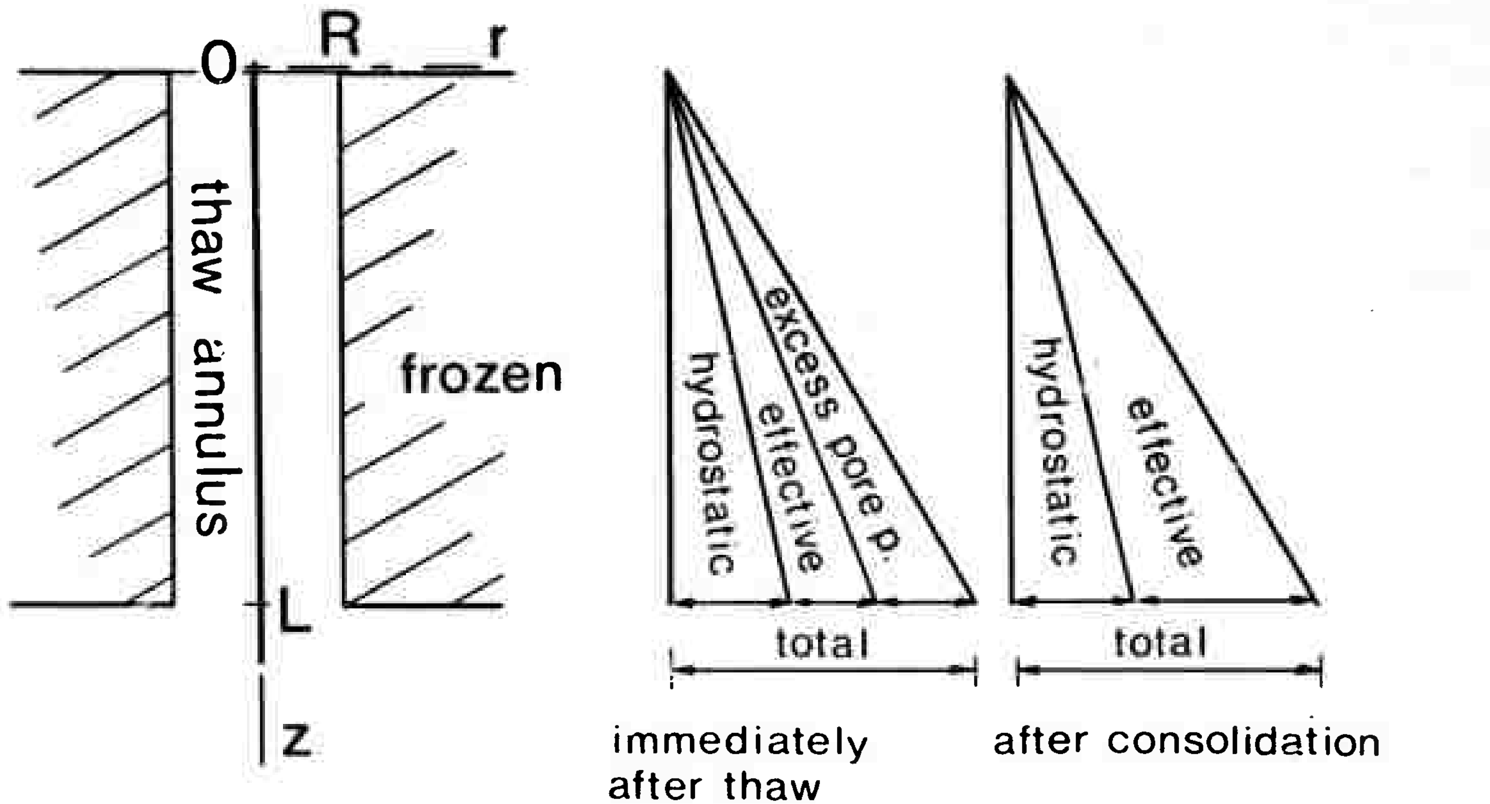


FIGURE 1


O
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thaw annulus
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FIGURE 2

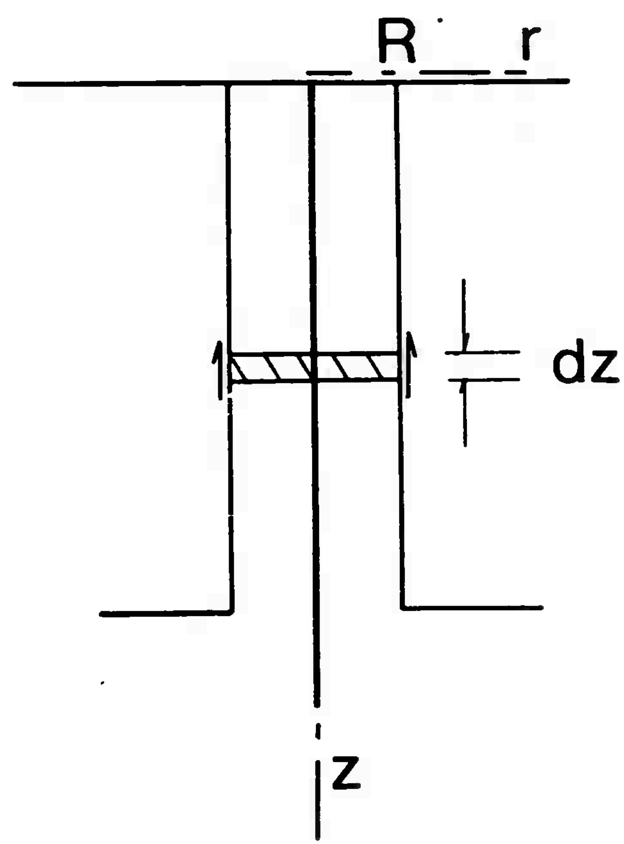
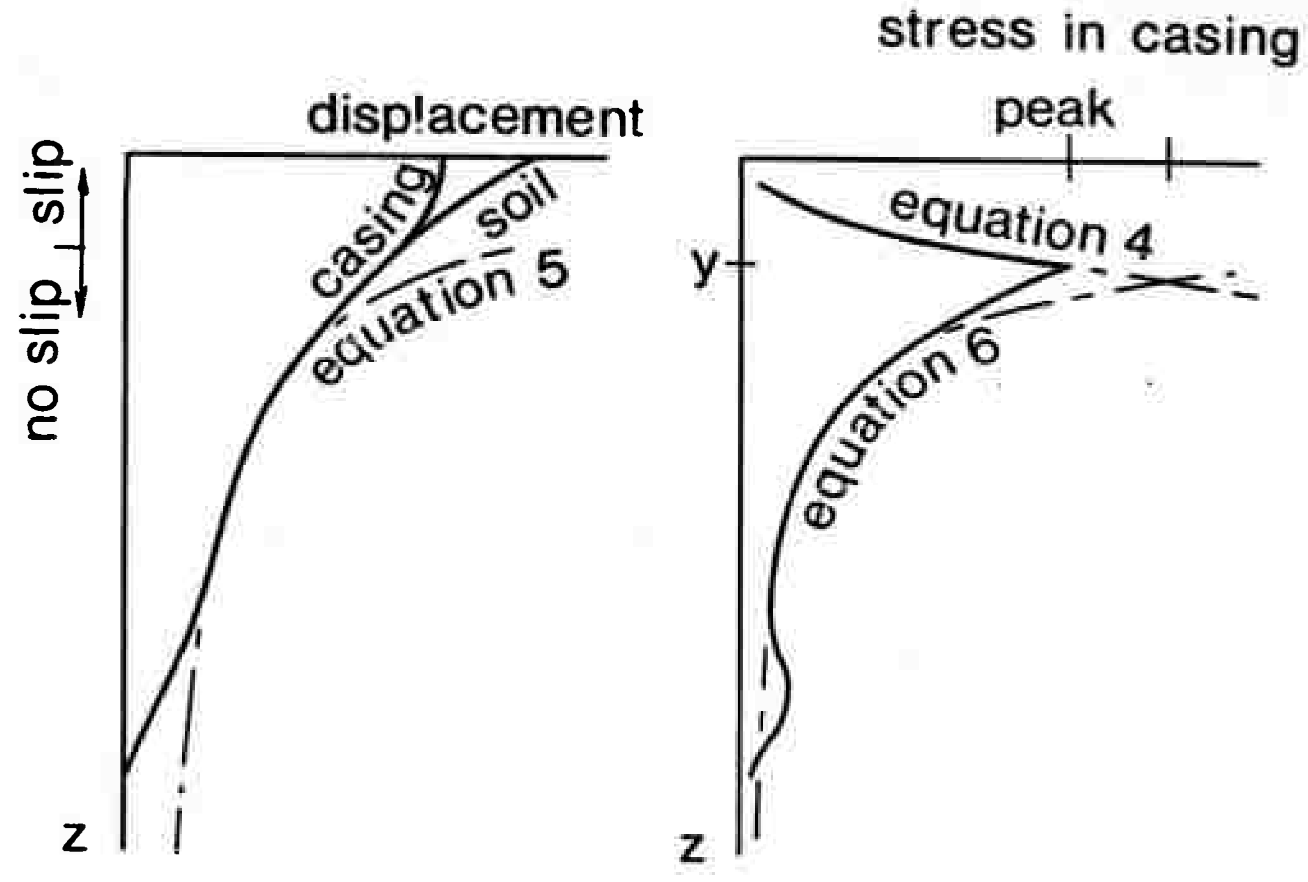


FIGURE 3


displacement
casing
soil
equation 5
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no slip
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stress in casing
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FIGURE 4